

DIGITAL RADIOSCOPIC EXAMINATION OF ANCIENT BRONZE CASTINGS

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ANCIENT CHINESE BRONZE RITUAL VESSELS

The Chinese aristocracy of the Shang (circa 1550 to 1030 B.C.) and Zhou (circa 1030 to 221 B.C.) dynasties commissioned the casting of sumptuous vessels in bronze for making ritual offerings of food and wine to their esteemed ancestors. The technical sophistication and extravagant consumption of raw materials required to produce these vessels attests to their importance as symbols of power for the ruling class. Enormous wealth was expended on the furnishing of tombs, in part because Chinese nobles believed that reverence for the needs of their ancestors in the afterlife would ensure the continued success of the clan on earth. Indeed such extravagance also served to legitimize the status of the ruling clans within Shang and Zhou society. Whether or not commissioned for specific tombs, bronze ritual vessels sooner or later ended up in burials where they survived for thousands of years.

The Cincinnati Art Museum's collection of ancient Chinese ritual bronzes is comprised of superb examples dating from the 13th to 6th centuries B.C. Most come from the area of the ancient Shang capital at Anyang (in modern Henan Province) and represent the classic phase of Shang Dynasty bronze production. Shang bronzes are characterized by complex surface adornment employing a design vocabulary of fantastic animal motifs unique to ancient China.

ANCIENT CHINESE CASTING TECHNIQUES

During the Shang Dynasty the Chinese developed a multi-stage process for casting bronze in sections of molded clay. First a model of the finished vessel was carefully carved in fine moist clay and then allowed to dry. The outer mold sections were produced by building up moist loess clay [1] around the model; this outer layer was then cut away in sections, fired and reassembled for pouring of the molten metal. Depending on the shape of the vessel being produced, the mold assembly needed one or more cores, also of clay, in addition to the outer mold parts. Metal spacers, or chaplets, were carefully placed between inner cores and outer mold parts to maintain the proper distance to create the desired vessel thick-

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ness. Vessels with legs were cast upside down so that the legs served as inlets for pouring the alloy of copper, tin and lead.

An alternative technique for casting bronze used in the ancient world was the lost-wax method, in which the model is made of wax and then melts away during the firing of the outer clay mold. This technique was known in the ancient Near East as early as the fourth millenium B.C. but was not employed in China until the 6th century B.C. [2], nearly 700 years after the vessels considered in this paper were produced. Even after Chinese metal-workers learned this method, they used it only for complex undercut shapes which would make removal of clay molds impossible, and continued to employ the clay section-mold technique they had perfected over many centuries.

Conservation of metal, a concern of the Near Eastern metal-worker because of scarce resources, was not a factor in China, where copper and tin were in abundant supply. Excavated fragments of clay section-molds reveal another factor which contributed to the success of the Chinese casting technique. Finely particled loess, borne on the winds from the Gobi desert and deposited over millions of years in the valley of the Yellow River (which flows through Henan Province), provided the ideal material for creating section molds which could accomodate the detailed carving needed to produce intricate surface ornament.

THE CINCINNATI ART MUSEUM'S CHINESE BRONZES

In January 1989, in the course of conducting research on the permanent collections, museum staff from the Conservation Department and the Department of Classical, Near Eastern and Far Eastern Art embarked on a project to analyze eight Chinese bronzes using X-radiography. The purpose of the analysis was to detect hidden repairs and damage in the vessels and to learn more about ancient casting techniques. Staff at General Electric Aircraft Engines (GEAE, Evendale, Ohio), when approached by the Museum, suggested that industrial computed tomography (CT), a new technology developed for scanning jet engine parts at GEAE's Quality Technology Center, be used rather than conventional X-radiography. Until now, museums analyzing ancient metalwork [3] have relied on conventional X-ray equipment. With this project the Cincinnati Art Museum in cooperation with the General Electric Company is pioneering new methods of art historical research through the use of industrial CT technology.

INDUSTRIAL COMPUTED TOMOGRAPHY [4]

Industrial computed tomography is an adaptation of computed axial tomography (or computer assisted tomography; popularly known as CAT-scanning), a non-destructive evaluation technique used in medicine. The CT scan allows imaging of the internal structure of an object, such as the human body, without having to cut it open. Analytical techniques that do not alter the object under study are obviously of considerable interest in the analysis of irreplaceable museum objects.

Medical CT scanners are designed to provide high-quality images of fairly large objects such as the human body, which have relatively low density and X-ray absorptivity. Beginning in the 1970's, soon after the initial development of medical CT systems [5], GE began work on development of industrial CT systems, with higher-energy X-ray sources and higher-resolution detectors and imaging systems. The first application was to inspection of small precision castings used in aircraft engines; through its NDE Systems and Services business, and through work done in its Quality Technology Center [6] for other GE businesses, GEAE has developed experience with a wide variety of other industrial applications.

CT systems use X-rays to sense properties of an object. However, unlike conventional radiography, which uses film to record an image, CT systems use electronic sensors to detect the X-rays which have traveled through the object being examined. The attenuation of the narrow fan-shaped X-ray beam as it passes through the object is directly related to the density, atomic number and thickness of the material, as well as to the energy of the X-ray beam. The digitized data are transferred via a data acquisition system to a high-speed computer which generates an image on a video terminal within a matter of seconds. Subsequent enhancement of the image can be achieved through the addition of color, by sharpening and enlarging, as well as by varying the brightness and contrast. A copy of the image can be printed or photographed. The image data can be stored on magnetic tape for later retrieval.

Two different types of images can be formed. The entire object can be quickly scanned to produce a digital radiograph (DR). The DR image, formed by translating the object relative to the beam, is similar to that obtained with conventional film radiography. Both compress the structural information from the three-dimensional object into a two-dimensional image. A computed tomograph (CT) image, formed by rotating the object relative to the X-ray beam, so that data can be collected from many different angles of view, provides a totally non-destructive cross-sectional view through the object. The thickness of the beam and the size of the sensing elements determine the thickness of the cross-sectional slice to be measured. In addition to a unique capability for examining internal structure without interference from protruding parts, and without confusion caused by the superposition of detail from different parts of the structure, CT is also unusually sensitive to variations in density or material composition. Precise dimensional measurement, with accuracy of the order of 0.001", is also possible.

Perhaps the most exciting possibility presented by this technology is the ability to reconstruct an accurate three-dimensional image of an object. By taking literally hundreds of contiguous CT slices and then compiling the data so that the individual slices effectively are stacked in sequence, a three-dimensional image can be created through computer processing techniques [7]. This computer model can be "cut up" electro-

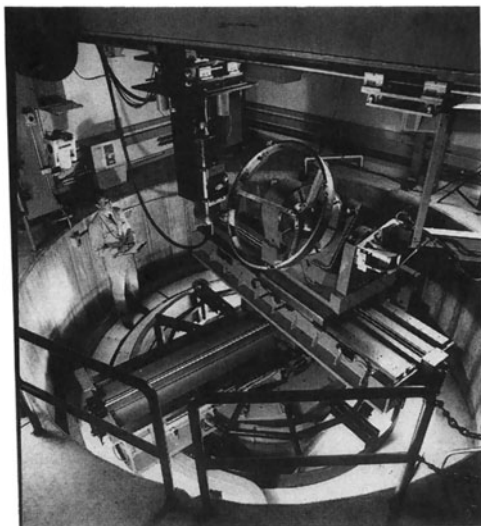


Figure 1. GE's ICT: an industrial CT system with multiaxis manipulator for examination of large fabricated components.

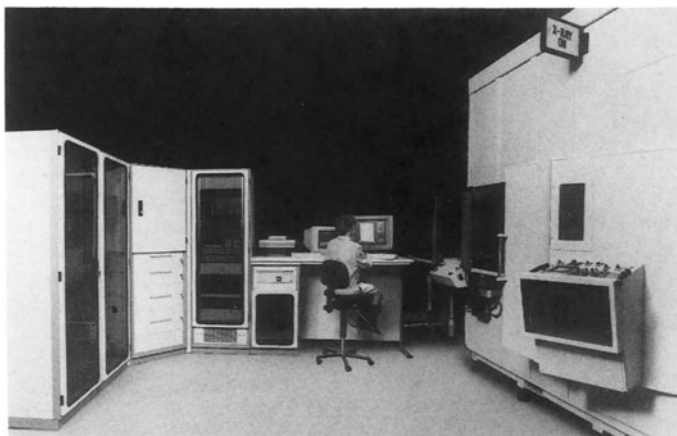


Figure 2. GE's XIM: an automated industrial CT system for examination of small components.



Figure 3. Sketches of typical Shang Dynasty bronze castings
a) jia b) jue c) guang

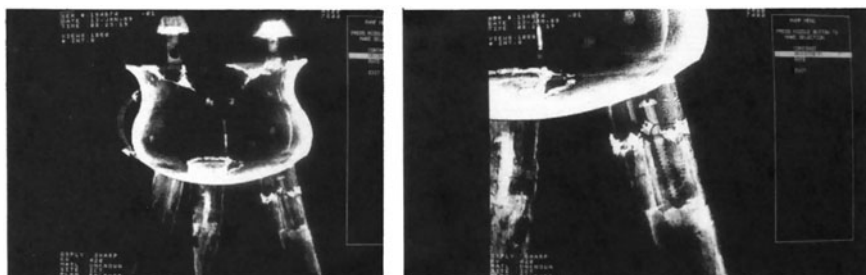


Figure 4. X-ray images of the jia showing repairs to two legs
a) DR image of entire vessel b) DR image of one leg

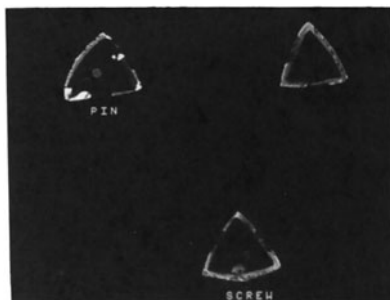


Figure 5. CT image through the legs of the jia

nically to enable the study of otherwise inaccessible interior surfaces or the structure of enclosed hollow vessels; in effect, the human eye can be placed inside a complex structure. Images of this type, formed by GE's Digital Replication™ process, were used to provide Museum staff with a unique insight into ancient casting technology.

RESULTS OF THE EXAMINATION OF CHINESE BRONZES [8]

GE Aircraft Engines maintains three high-resolution CT scanning systems for industrial applications in its Cincinnati-area facilities: two of these units are shown in Figures 1 and 2. Available X-ray source energies are 160 kV, 420 kV, and 2 MV. For examination of the eight Art Museum bronzes, three of which are illustrated in Figure 3, a source energy of 420 kV was used, with a slice thickness of 0.020".

The jia, a tripod vessel used for ceremonial warming of wine, revealed the most startling condition problems of the eight bronzes analyzed. From the DR images (Figure 4), numerous repairs -- on the handle, in the legs, and along the rim -- were detected; these areas appear as bright white in the images, corresponding to high contrast in material density, associated with the probable use of a lead-tin solder. Two of the legs have major repairs. One leg was reassembled using a modern screw, indicating that the object was probably repaired shortly before the Museum purchased it in 1948. Another leg has a less obvious break, and was reassembled using a metal pin. This repair appears older and may have been performed in antiquity -- a "factory recall", perhaps -- since no evidence of the break is visible on the surface; it is completely concealed by patination accumulated during its extended burial. CT scans taken through the legs (such as Figure 5) show the exact location of the screw and pin with respect to the interior walls of the legs. A CT scan taken where the legs join the vessel body revealed the reattachment of one leg.

Small tripod vessels with slender legs, such as the jue (Figure 6), were cast upside down in a single pour. Clearly visible in both the DR (Figure 7) and CT images are concentrations of trapped air bubbles in the rounded bottom of the vessel, illustrating the porosity problems ancient artisans encountered in working with molten metal. One of the fortuitous qualities of the loess used by the Chinese for section molds is its ability to absorb trapped gases which could otherwise have pitted the surface of castings. The CT scans show how close to disaster this casting came; the very nature of the mold material probably saved this vessel from failure.



Figure 6. Photograph of jue

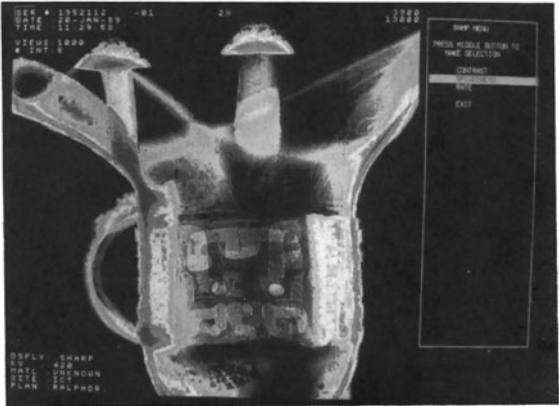


Figure 7. DR image of jue

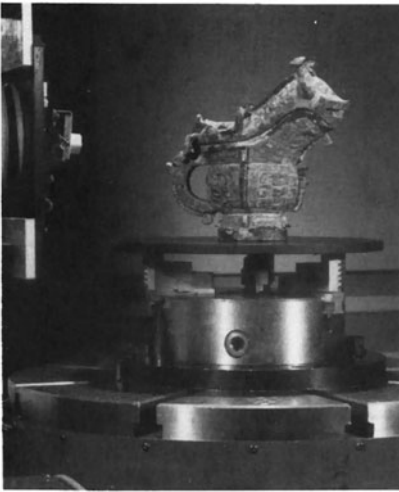


Figure 8. Guang mounted on ICT manipulator

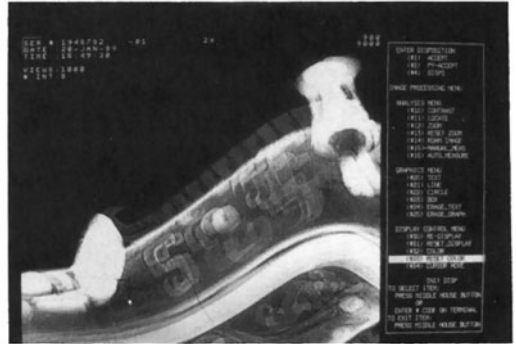


Figure 9. DR image of guang showing hairline fracture of lid

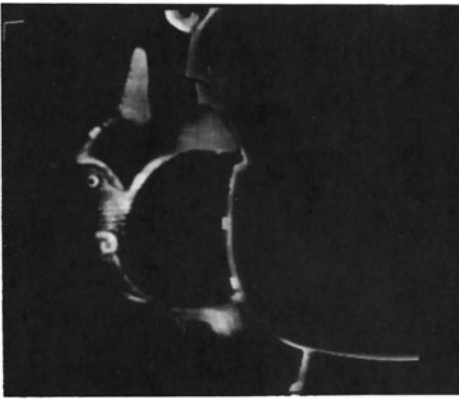


Figure 10. CT image through bowl and handle of the guang



Figure 11. Digital Replication image of guang showing interior of handle

A lidded wine vessel in the form of composite fantastic animals, of the type known as guang (Figure 8), represents the most complex casting of the eight bronzes analyzed. DR images reveal only one condition problem, a hair-line fracture in the center of the lid (Figure 9). A close-up DR image of the guang handle revealed that it was cast around a clay core. CT scans taken through the handle (Figure 10) showed core shape and wall thickness in those locations, as well as confirming the presence of tenons extending from the body for the handle's attachment. Visual evidence of metal overflow onto the surface decoration of the body confirms that the handle was cast on as a separate unit.

In order to fully characterize the configuration of the clay core and to determine the nature of the join between the handle of the guang and its body, a three-dimensional model was constructed by taking CT

slices horizontally through the entire vessel at 0.020" increments. By slicing the "electronic model" in half lengthwise, and rotating it on the screen, the interior of the handle was exposed (Figure 11), revealing the shape of the clay core inside with near-photographic resolution.

Among the manipulations possible with three-dimensional replication is the ability to create a synthetic CT image in an arbitrary plane through the vessel, using data accumulated during previous scanning. This proved useful in analysis of the guang. Synthetic CT images were created vertically through the handle. The resulting images, when combined with horizontal CT and DR views, provided a full characterization of the join, confirming suspicions that the handle was indeed cast on over tenons extending from the already formed body.

SUMMARY

The technical sophistication achieved by early Chinese bronze casters was unsurpassed in the ancient world. The eight vessels examined in this project represent state-of-the-art casting technology of 3000 years ago. Through the application of sophisticated industrial non-destructive evaluation techniques, providing safe examination methods to aid in the preservation of these amazing works of art, this encounter of modern technology and art history has advanced the knowledge of ancient metallurgical practices.

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